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Analysis of Spatial Variability in the Depth of the Water Table in Grassland Areas

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1. Introduction

The availability of water is one of the main drivers of the natural environment, and it depends on a number of factors. Meteorological conditions decisively affect the water conditions. Temporal variability in the distribution of rainfall in an area will contribute to variability in water conditions in the area. A drought or flood occurs in Poland every five years, on average (Lipiński 2003, Mioduszewski 2003).

Many phenomena have to be taken into account when forecasting variations in groundwater levels in irrigated areas within valleys. Most studies of soil water have involved making measurements at selected points or along selected transects. Little research has been performed on water feeding into deep drainage in basins in reclaimed areas (Grzywna 2011, Nyc & Pokładek 2004).

Kriging is a technique that allows optimal and unbiased estimates of regionalized variables at unstapled locations to be made using the structural properties of a semivariogram and an initial dataset (Kumar & Remadei 2006). Kriging takes into consideration the spatial structure of a parameter, so it produces better estimates than do other methods, such as the arithmetic mean method, the nearest neighbor method, the distance weighted method or the polynomial interpolation method. Kriging provides the estimated variance at each point for which an estimate is provided and this variance indicates the accuracy of the estimated value. This is considered to be the main advantage of using kriging over using other estimation techniques (Fen et al. 2004, Gundogdu & Guney 2007).

The basic concepts involved in the kriging technique and the use of the kriging technique to analyze natural phenomena have been reviewed by the ASCE Task Committee. Kriging has been used in the fields of soil science (Bardossy & Lehmann 1998), hydrology (Germann & Joss 2001) and atmosphere science (Merino et al. 2001). Kumar (2007) and Kumar & Ahmed (2003) have used the kriging technique to analyze groundwater levels. It is necessary to estimate groundwater levels at points on a regular grid from measurements at random points covering the area of interest to allow groundwater simulation models to be produced. These models can be used to support the sustainable management of groundwater, which is a precious resource.

The objective of study was to evaluate the applicability of the kriging method for the analysis of the groundwater level.

2. Materials and methods

In the study presented here, we determined the spatial distribution of the groundwater levels in grassland in irrigated microcatchments in the River Piwonia valley in Sosnowica. The study area is in Eastern Poland in the province of Lublin (Fig. 1) and has a climate with temperature extremes of -30°C and 35°C (average 8°C). The annual rainfall in the area is about 600 mm, 40% of which occurs between June and September, and the evapotranspiration potential is high (Grzywna 2011). The geology of the area is marked by extensive sandy plains of aeolian sand and alluvium from the Quaternary age. The alluvium is mostly fluvial in origin and comprises unconsolidated to loosely consolidated sediments consisting of alternate sequences of sand, peat, and kankar, with occasional gravel horizons. The main soil types in the study area are histosols and gleysols. Groundwater in these alluvial sediments occurs as a water table, which is saline over most of the study area.

Water variability in the drainage area for ditch K-2, which discharges surface water into the River Piwonia, was studied. This drainage area is in the village of Sosnowica in Western Polesie. The drainage area is 0.46 km^2, and 86% of the area is grassland that was once semi-natural, the remaining 14% being birch and pine woodland. Boggy habitats make 0 up 75% of the basin, and these habitats are characterized by high groundwater levels and little variability in water retention characteristics.

The catchment area of the ditch has a very slight slope, of 1.1%, and the area contains a flat-bottomed valley. The depth of the groundwater table was measured in 15 piezometric wells in the grassland in the study area every 30 days in vegetation period (7 measurements times). The dataset consists of groundwater levels measured at the 15 points in three tests series grouped by season of the year: spring (series I), summer (series II) and autumn (series III).

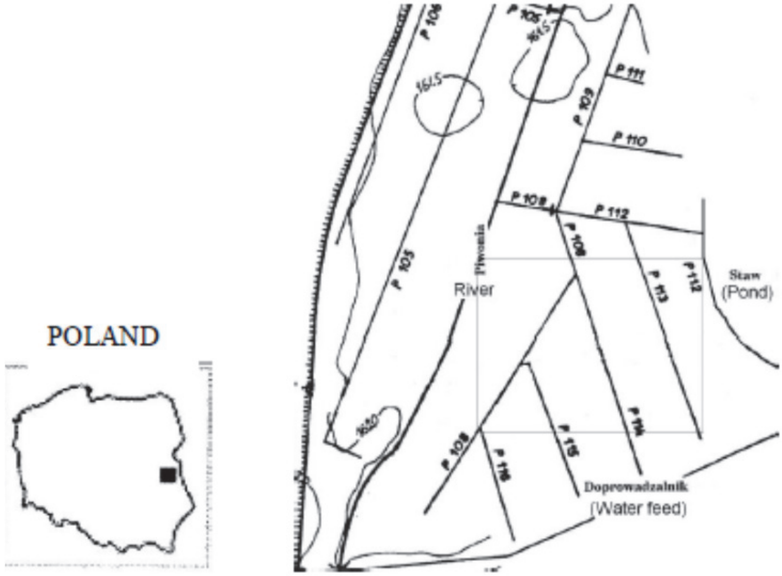

Fig. 1. Location of research area, P105-P116 – ditches
Rys. 1. Lokalizacja obszaru badań, P105-P116 – rowy

The depth of the groundwater level would have depended on the amount of evaporation that had occurred, and would have affected the characteristics of the hydrographic network. The water depths were smallest at the beginning of the growing season and greatest at the height of summer. The groundwater levels were most stable in the autumn, as has been found in previous studies (Przybyła et al. 2013). Kriging techniques which have been well documented (Diodato & Ceccarelli 2005, Krivoruchko 2006) was used in analysis. Estimation of spatial autocorrelation in kriging technique is based on the experimental semivariogram (Zawadzki 2011).

Various theoretical models, such as spherical, exponential, and Gaussian models, were fitted to the semivariograms for the study data, and the model that gave the lowest standard error was used to perform further analyses. The strength of the fitting the model to the data were checked in validation tests using a 'jackknifing procedure', in which kriging was performed repeatedly for all of the data points except one (with a minimum standard error). The first point was excluded in the first stage of the procedure, then each subsequent point was excluded in turn in the subsequent stages of the procedure. The differences between the estimated and observed values were summarized using cross-validation statistics (Kitanidis 1997, Krivoruchko 2006).

The cross-validation procedure involved sequentially omitting a datapoint and predicting its value using the remaining data, then comparing the measured and predicted values for each datapoint. The results of the procedure were used to indicate whether the model could reasonably be used to produce a map (Kumar & Remadei 2006, Lakhankar et al. 2010). The differences between the estimated and observed values were summarized using five cross-validation statistics, which were the mean prediction error, the root-mean-square prediction error, the average kriging standard error, the mean standardized prediction error, and the root-mean-square standardized prediction error (Fischer et al. 1996, Nikroo et al. 2010, Kresic & Mikszewski 2013).

If the semivariogram model and the kriging procedure adequately reproduced the observed values, the summary statistics would have satisfied the criteria given below and described in other publications (Namysłowska-Wilczyńska 2006, Uyan & Cay 2013).

Kriging is an exact interpolation estimator that can be used to find the best linear unbiased estimate. The best linear unbiased estimate must have a lower estimate error variance than the other linear estimates have. We used the ordinary kriging method because of its simplicity and the accuracy of its predictions compared with the accuracy of other kriging methods. Ordinary kriging is also one of the most popular kriging methods used in hydrological studies (Araghinejad & Burn 2005).

The geographic information system (GIS) software package ArcGIS 10 and the ArcGIS Geostatistical Analyst extension were used to perform the ordinary kriging estimates. The maps were produced using the ArcMap module in ArcGIS.

3. Results

The descriptive statistics of the observed groundwater levels are shown in Table 1. The depth of the groundwater level in 2012 ranged from 3 cm (in test series I and II) to 103 cm (in test series III). The groundwater depth was smallest at the end of March (caused by the thawing of the soil) and in July (after heavy rain). The mean depth of the groundwater level was 39.93 cm in test series I and 33.40 cm in test series II. The depth of the groundwater level was greatest at the end of September, when the mean depth was 67.67 cm. The smallest groundwater level depth was found near the Hetman fish pond in all of the test periods. The greatest groundwater level depth was found near the river Piwonia, because there was a 2 m deep drainage bed in this area.

Table 1. General statistics of groundwater level for the test series
Tabela 1. Podstawowe statystyki poziomu wody gruntowej dla serii testowych

Series of tests	Mean [cm]	Standard deviation [cm]	Variation coefficient [-]	Median [cm]	Minimum [cm]	Maximum [cm]
I	39.93	23.44	0.59	37.00	3.00	74.00
II	33.40	22.19	0.66	27.00	3.00	70.00
III	67.67	21.60	0.32	68.00	37.00	103.00

The smallest coefficient of variation (0.32) was found for test series III and the highest coefficient of variation (0.66) was found for test series II. The Gaussian model gave the lowest standard error for each dataset, so it was considered to give a better fit than the other models. The theoretical fitted Gaussian semivariograms for three sets of data had the forms presented in figure 2.

The Gaussian model fitted to all of the datasets better than did the other models, but the Gaussian model parameters were different for the different datasets (i.e., they changed over time). The nugget effect varied between 0.52 and 154.91, and the partial sill values were 525.44, 347.3, and 518.43 for test series I, II, and III, respectively, with ranges of 203.5, 213.44, and 300, respectively. This means that the groundwater level in the study area was autocorrelated in the distance between 203.5 m and 300 m.

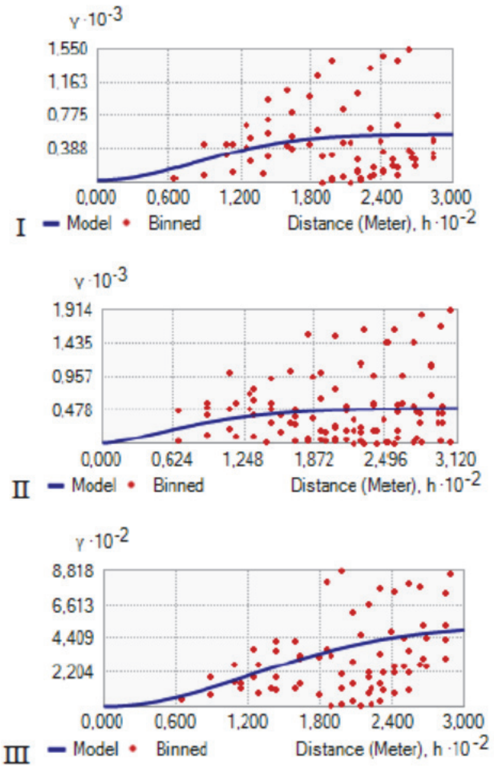

Fig. 2. Semivariograms for the three test series
Rys. 2. Semiwariogramy dla trzech serii testowych

The performances of the predictions were assessed using the cross-validation technique, in which the accuracy of the surface generated was examined. The cross-validation results that were used to determine the validity of the fitted model and the semivariogram parameters are shown in Table 2. The jackknifing procedure results showed that the selected model and its parameters adequately described the measured data.

Table 2. Cross validation results for the Gaussian model
Tabela 2. Wyniki walidacji krzyżowej dla rozkładu Gaussa

Series	ME	RMSE	MSE	RMSSE	AKSE
I	-1.4	8.94	-0.07	0.62	14.43
II	-1.57	16.16	-0.06	0.88	18.13
III	-1.16	4.99	-0.20	1.01	4.55

I

II

III

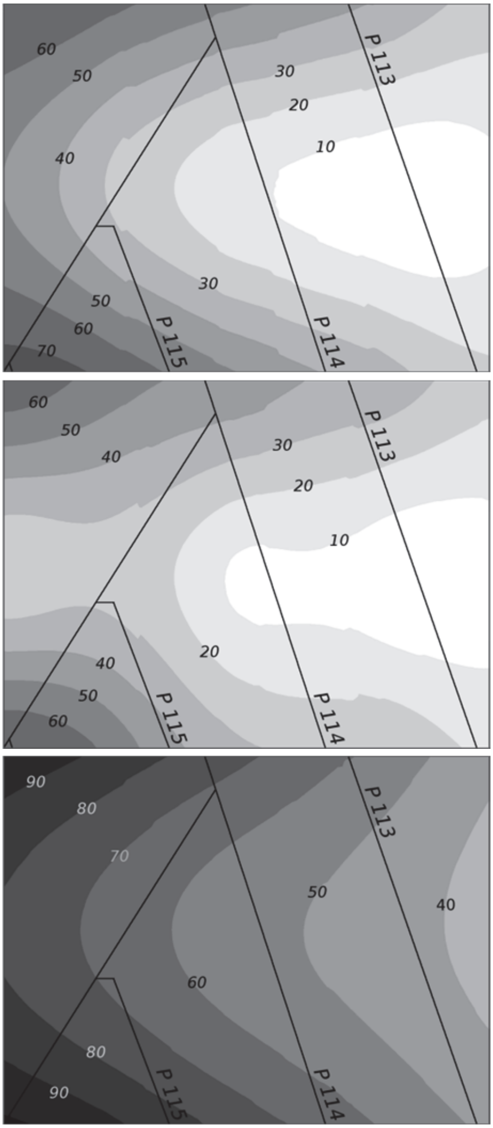

Fig. 3. Predicted spatial variability of groundwater level in spring (I), summer (II) and autumn (III)
Rys. 3. Przewidywana przestrzenna zmienność poziomu wody gruntowej wiosną (I), latem (II) i jesienią (III)

The spatial distributions of the groundwater level in the study area in the three test series are shown in figure 3. The shallowest groundwater level was found in the vicinity of the Hetman fish pond throughout the study period. This was because surface water seeped into the soil in that area. The depth of the groundwater level gradually increased moving westward, and was greatest in the vicinity of the River Piwonia, especially near the north and south P112 ditches and the dry water feed.

4. Conclusions

Geostatistics and GIS are well established techniques that are currently used in different fields. Integrating or coupling these systems would benefit both workers using GIS and workers using geostatistics, by increasing the scope for spatial analysis for those currently using GIS and by providing overlay and data manipulation facilities to aid the interpretation of results for those currently using geostatistics. The geostatistical analysis in this study was performed using ArcGIS software, and the spatial distributions of fluctuations in groundwater levels were also studied.

The ordinary kriging geostatistical technique was used to analyze groundwater level data from three test series performed in Sosnowica. The model was validated using cross-validation statistics. Groundwater levels maps were produced to illustrate the spatial variations in the groundwater levels in the study area.

In spring and summer, flooding of grassland in the eastern part of the study area was observed. It was caused by seepage of water from the pond and the supply of water after ice thawing or after rainfall. The obstruction of drainage including neglected ditches had also impact on flooding. The groundwater level in the western part of the study area decreased excessively in the fall because of drainage effect of the river which depth is about 2 m.

The spatial analysis of the groundwater level data from the 15 piezometers led to the following conclusions:

- groundwater level in the study area were autocorrelated in the distance between 203.5 and 300 m depending on year season,
- the groundwater level depth was smallest in the vicinity of the Hetman pond and greatest near the River Piwonia,
- the Gaussian model best represented the spatial variability in the groundwater levels.

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Analiza zmienności przestrzennej głębokości położenia wód gruntowych na użytkach zielonych

Streszczenie

Do analizy zmienności przestrzennej poziomu zalegania wód gruntowych na nawadnianych użytkach zielonych w dolinie zlewni rzeki Piwonia wykorzystano technikę przestrzennej analizy statystycznej w postaci krigingu. W prezentowanych badaniach analizę geostatystyczną obejmującą studium rozkładu przestrzennego wahań głębokości położenia wód gruntowych przeprowadzono przy użyciu oprogramowania ArcGIS. Celem pracy była ocena możliwości stosowania metody krigingu do analizy poziomu wody gruntowej.

Wykorzystane zostały dane obserwacyjne zebrane w rejonie Sosnowicy w 2011 roku (Polesie Lubelskie). Badany obszar położony jest we wschodniej Polsce, w województwie lubelskim i charakteryzuje się klimatem umiarkowanym z ekstremalnymi temperaturami od -30°C do 35°C (średnia 8°C). Suma opadów rocznych na obszarze badań wynosi około 600 mm, z czego 40% ma miejsce w okresie od czerwca do września, a potencjalna ewapotranspiracji jest wysoka. Powierzchnia zlewni rowu wynosi 0,46 km^2 i jest w 86% użytkowana jako jednokośne półnaturalne łąki. W pokrywie glebowej dominują zdegradowane gleby murszowo-torfowe (MtII). 75% powierzchni stanowią siedliska pobagienne i wilgotne charakteryzujące się wysokim poziomem wody gruntowej w glebie.

Podtapianie łąk we wschodniej części obszaru badań na wiosnę i w lecie jest spowodowane filtracją wody ze stawu, doprowadzaniem wody i niedrożnością systemu melioracyjnego w trakcie roztopów lub ulewnych opadów deszczu. Z kolei w zachodniej części badanego obszaru poziom wód gruntowych nadmiernie się obniża z powodu drenującego działania rzeki, której głębokość wynosi 2 m.

Zbiór analizowanych danych dotyczył poziomów wód gruntowych mierzonych w 15 punktach w trzech okresach badawczych (wiosna, lato, jesień). Pomierzone poziomy wody gruntowej zostały wykorzystane do skonstruowania semiwariogramów eksperymentalnych charakteryzujących poziomą zmienność przestrzenną. Gama modeli teoretycznych (model sferyczny, wykładniczy i Gaussa) została dopasowana do semiwariogramów eksperymentalnych. Modele zostały sprawdzone za pomocą statystyki krzyżowej. W celu ilustracji zmian przestrzennych głębokości położenia wód gruntowych na obszarze badań utworzone zostały mapy hydroizohips. Analiza przestrzenna danych poziomu wód gruntowych z piezometrów doprowadziła do następujących wniosków:

- autokorelacja poziomu wód gruntowych w obszarze badań ma zasięg od 203,5 do 300 m – zależnie od serii,
- głębokość położenia zwierciadła wód gruntowych była najmniejsza w pobliżu stawu Hetman, a największa w pobliżu rzeki Piwonia,
- przestrzenna zmienność głębokości położenia wody gruntowej dla wszystkich serii badań była lepiej opisana przez model Gaussa niż przez inne modele.

Abstract

The kriging spatial statistical analysis technique was used to analyze spatial variability in the groundwater levels in irrigated grassland catchment in the Piwonia River valley. The geostatistical analysis in this study was performed using ArcGIS software, and the spatial distributions on fluctuations in groundwater levels were also studied. The objective of study was to evaluate the applicability of the kriging method for the analysis of the groundwater level.

Field observation data collected in Sosnowica in 2011 were used (Western Polesie). The study area is located in Eastern Poland in the province of Lublin and has an temperate climate with temperature extremes -30°C and 35°C

(average 8°C). The annual rainfall in the area is about 600 mm, 40% of which occurs between June and September, and the evapotranspiration potential is high. The catchment area of the ditches is 0.46 km^2 and is 86% of area is used as a one-crop seminatural meadows land. The soil cover is dominated by degraded soil muck-peat (MtII). In the catchment area 75% of the habitat moorshed and moist with a high groundwater level.

In spring and summer, flooding of grassland in the eastern part of the study area was observed. It was caused by seepage of water from the pond and the supply of water after ice thawing or after rainfall. The obstruction of drainage including neglected ditches had also impact on flooding. The groundwater level in the western part of the study area decreased excessively in the fall because of drainage influence of the river which depth is 2 m.

The dataset consisted of groundwater level measured at 15 points in three test periods (spring, summer and autumn). The measured groundwater levels were used to construct experimental semivariograms to characterize the spatial variability in the levels. A range of theoretical models (spherical, exponential, Gaussian models) were fitted to the experimental semivariograms. The models were validated using cross-validation statistics. Surface generated hydroizohipses maps were produced to illustrate spatial variations in the groundwater level in the study area. The spatial analysis of the groundwater level data from the piezometers led to the following conclusions:

- groundwater levels in the study area were autocorrelated in the distance between 203.5 and 300 m – depending on series,
- the groundwater level depth was smallest in the vicinity of the Hetman pond and greatest near the Piwonia river,
- spatial variability in the groundwater levels was described better by the Gaussian model than by the other models for all test series.

Słowa kluczowe:
geostatystyka, poziom wody gruntowej, semiwariogram, kriging

Keywords:
geostatistics, groundwater levels, semivariogram, kriging